9.0 Earth's Magnetism

An ordinary compass works because the Earth is itself a giant magnet with a north and a south pole. Navigators have known about the pole-seeking ability of magnetized compass needles and lodestone for thousands of years. During the last two centuries, much more has been learned about the geomagnetic field, and how it shapes the environment of the Earth in space.

The geomagnetic field is believed to be generated by a **magnetic dynamo** process near the core of the Earth through the action of currents in its outer liquid region. Geologic evidence shows that it reverses its polarity every 250,000 to 500,000 years. In fact, the geomagnetic field is decreasing in strength by 5% per century, suggesting that in a few thousand years it may temporarily vanish as the next field reversal begins. Although the geomagnetic field deflects high-energy cosmic rays, past magnetic reversals have not caused obvious biological impacts traceable in the fossil record. Earth's atmosphere, by itself, is very effective in shielding the surface from cosmic rays able to do biological damage. The location of the magnetic poles at the surface also wanders over time at about 10 kilometers per year. Mapmakers periodically update their maps to accommodate this drift.

The domain of space controlled by Earth's magnetic field is called the **magnetosphere**. The geomagnetic field resembles the field of a bar magnet, however there are important differences due to its interaction with the **solar wind**: an interplanetary flow of plasma from the Sun. The magnetosphere is shaped like a comet with Earth at its head. The field on the dayside is compressed inwards by the pressure of the solar wind. A boundary called the **magnetopause** forms about 60,000 kilometers from Earth as the solar wind and geomagnetic field reach an approximate pressure balance. The field on the night side of Earth is stretched into a long **geomagnetic tail** extending millions of kilometers from Earth. Above the polar regions, magnetic field lines from Earth can connect with field lines from the solar wind forming a **magnetospheric cusp** where plasma and energy from the solar wind may enter. Ionized gases from Earth's upper atmosphere can escape into the magnetosphere through the cusp in gas outflows called **polar fountains**. The magnetosphere is a complex system of circulating currents and changing magnetic conditions often affected by distant events on the Sun called "space weather." The conveyor belt for the worst of these influences is the ever-changing solar wind itself. Space weather "storms" can trigger changes in the magnetospheric environment, cause spectacular aurora in the polar regions, and lead to satellite damage and even electrical power outages.

9.1 Trapped Particles and other Plasmas

Within the magnetosphere there are several distinct populations of neutral particles and plasmas. The **Van Allen Radiation Belts** were discovered in 1958 during the early days of the Space Age. The inner belts extend from altitudes between 700 to 15,000 km and contain very high-energy protons trapped in the geomagnetic field. The outer belt extends from 15,000 to 30,000 km and mostly consists of high-energy electrons. Geosynchronous satellites orbit Earth just outside the outer belt. Human space activity is confined to the zone within the inner edge of the inner belt. Space suited astronauts exposed to the energetic particles in the Van Allen Belts would receive potentially lethal doses of radiation. The particles that make up the Van Allen Belts bounce along the north and south-directed magnetic field lines to which they are trapped like water flowing in a pipe. At the same time, there is a slow drift of these particles to the west if they are positively charged, or east if they are negatively charged. There are also three additional systems of particles that share much the same space as the Van Allen Belts, but have much lower energies: the geocorona; the plasmasphere; and the ring current.

Extending thousands of kilometers above Earth is the continuation of its tenuous outer atmosphere called the **geocorona**. It is a comparatively cold, uncharged gas of hydrogen and helium atoms whose particles carry little energy. In the geocoronal region, there is a low-energy population of charged particles called the **plasmasphere** which are a high-altitude extension of the ionosphere. Unlike the geocorona, the plasmasphere is a complex, ever-changing system controlled by electrical currents within the magnetosphere. These changes can cause this region to fill up with particles, and empty, over the course of hours or days.

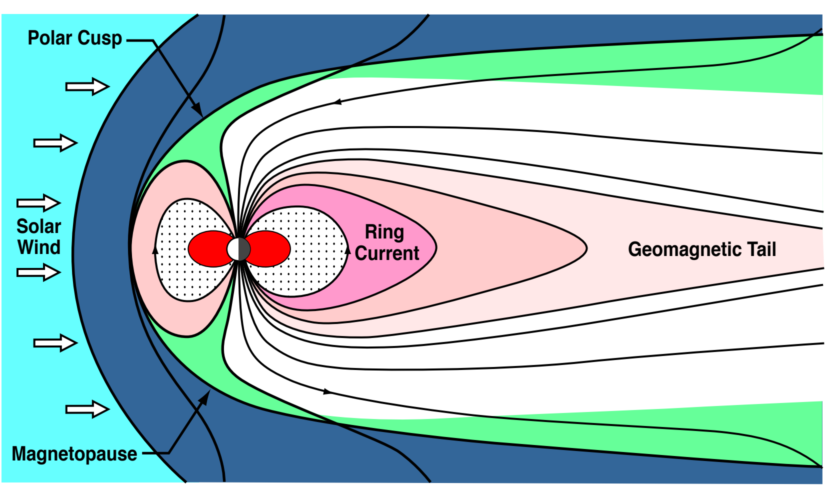

Figure 5-1 Earth's Magnetic Field.

The geomagnetic field resembles the field of an ordinary bar magnet. The north magnetic pole of Earth is located near the south geographic pole while the south magnetic pole of Earth is located near the north geographic pole. The figure also shows the major regions of Earth's magnetosphere. The dotted region contains the Van Allen Radiation Belts. The red region is the plasmasphere.

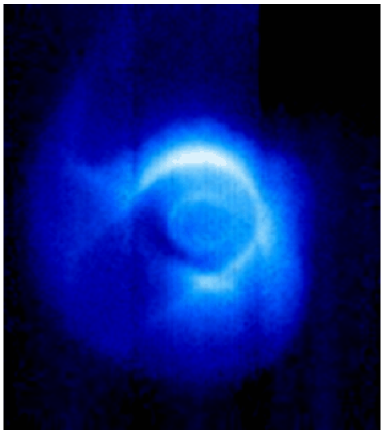

Figure 5-2 The Plasmasphere. A view from above the North Pole of the plasmasphere illuminated by ultraviolet light from the Sun. The Sun is located beyond the upper right corner.

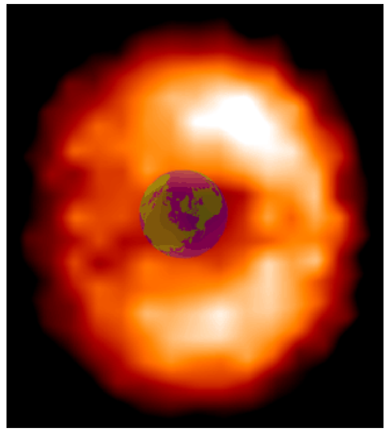

Figure 5-3 The Ring Current. From above the North Pole, the current is seen flowing around the equatorial regions of the Earth.

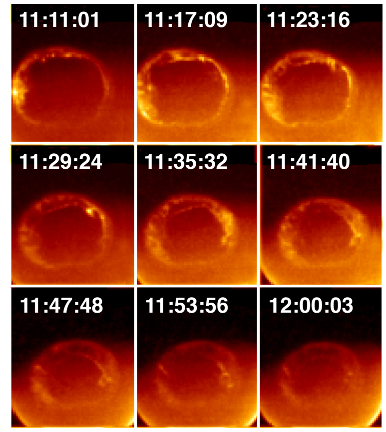

Figure 5-4 The Auroral Oval. From space, the aurora borealis appears as a ring of light that changes its appearance from minute to minute.

During severe storms, compasses display incorrect bearings as the surface geomagnetic field changes its direction. In the equatorial regions, an actual decrease in the strength of the geomagnetic field can often be measured. This is generally attributed to the existence of a temporary river of charged particles flowing between 6,000 to 25,000 kilometers above ground: the **ring current**. These particles have energies between those within the plasmasphere and those in the Van Allen Belts. They appear to originate within the geomagetic tail as charged particles that are injected deep into the magnetosphere. Most of the time there are few particles in the ring current, but during severe storms, it fills up with a current of millions of amperes which spread into an invisible ring encircling Earth. Just as a flow of current through a wire creates its own magnetic field, the ring current generates a local magnetic field that can reduce some of Earth's surface field by up to 2% over the equatorial regions.

In addition to these families of particles, there are also powerful currents of particles that appear during especially stormy conditions, and lead to visually dramatic phenomena called the **aurora borealis** and the **aurora australis:** the Northern and Southern lights.

9.2 The Aurora

For thousands of years humans have been able to look up at the northern sky and see strange, colorful, glows of light. By the early 1900's, spectroscopic studies had shown that auroral light was actually caused by excited oxygen and nitrogen atoms emitting light at only a few specific wavelengths. The source of the excitation was eventually traced to currents of electrons and protons flowing down the geomagnetic field lines into the polar regions where they collide with the atmospheric atoms. However, aurora are not produced directly by solar flares. Radio communications blackouts on the dayside of Earth are triggered by solar flares as these high-energy particles disturb the ionosphere. When directed toward Earth, expulsions of matter by the Sun called **coronal mass ejections** contribute to the conditions that cause some of the strongest aurora to light up the skies. At other times, a simple change in magnetic polarity of the solar wind from north-directed to south-directed seems to be enough to trigger aurora without any obvious solar disturbance.

Because of the existence of the magnetospheric cusp on the dayside of Earth, solar wind particles can, under some conditions, flow down this entryway into the polar regions. This causes daytime aurora, or the diffuse red glows of nightime auroras. This is, virtually, the only instance where solar wind particles can directly cause aurora. It is not, however, the cause of the spectacular nightime polar aurora that are so commonly photographed. To understand how these aurora are produced, it is helpful to imagine yourself living inside a television picture tube. We don't see the currents of electrons guided by magnetic forces, but we do see them paint serpentine pictures on the atmosphere, which we then see as the aurora. The origin of these currents is in the distant geomagnetic tail region, not in the direct inflow of solar wind plasma.

When the polarity of the solar wind's magnetic field turns southward, its lines of force encounter the north-directed lines in Earth's equatorial regions on the dayside. The solar wind field lines then connect with Earth's field in a complex event that transfers particles and energy into Earth's magnetosphere. While this is happening near Earth, in the distant geomagnetic tail, other changes are causing the geomagnetic field to stretch like rubber bands, and snap into new magnetic shapes. This causes billions of watts of energy to be transferred into the particles already trapped in the magnetosphere out in these distant regions. These particles, boosted in energy by thousands of volts, then flow down the field lines into the polar regions to cause the aurora, like the electrons in a television picture tube that paint a pattern on the phosphor screen.